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ADVISORY GROUP FOR AERONAUTICAL RESEARCH AND DEVELOPMENT

64 RUE DE VARENNE, PARIS VII

REPORT 429

**INVESTIGATIONS ON THE
GROUND PERFORMANCE OF AIRCRAFT
RELATING TO WET RUNWAY BRAKING
AND SLUSH DRAG**

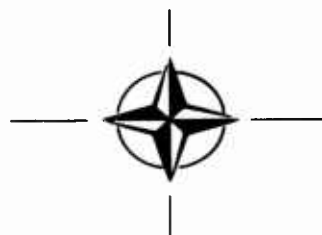
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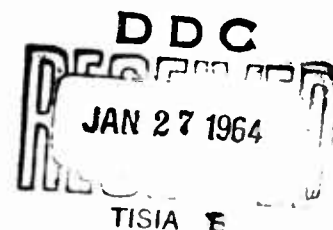
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NORTH ATLANTIC TREATY ORGANIZATION



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REPORT 429

NORTH ATLANTIC TREATY ORGANIZATION
ADVISORY GROUP FOR AERONAUTICAL RESEARCH AND DEVELOPMENT

INVESTIGATIONS ON THE GROUND PERFORMANCE OF AIRCRAFT
RELATING TO WET RUNWAY BRAKING AND SLUSH DRAG

by

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and

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This Report was presented at the Aircraft Take-Off and Landing Specialists' Meeting
sponsored by the AGARD Flight Mechanics Panel, held in Paris, 15-18 January 1963

SUMMARY

A review is made of recent research in the United States relating to the ground performance of aircraft. Since many of the investigations have been conducted at the NASA Landing Loads Track at the Langley Research Center, a brief description of the track and its capabilities is given. Various factors affecting landing and take-off distances are discussed, such as the runway surface conditions, whether dry, wet, or covered with slush, and the tire tread pattern and its state of wear. Performance calculations are presented for a typical jet transport showing the effect of runway slush on the take-off distance; also shown are the effects of tire-to-runway braking coefficients on landing runout distances. The Report concludes with indications of areas of interest for future research.

SOMMAIRE

On passe en revue les récents travaux de recherche aux Etats-Unis au sujet des performances des avions au sol. Etant donné que bon nombre des enquêtes ont été menées au NASA Landing Loads Track du Centre de Recherche Langley, il est fourni ici une brève description de cette piste et de ses capacités. On discute de divers facteurs intéressant les distances d'atterrissage et de décollage, par exemple les états de surface des pistes, à savoir sèches, mouillées ou couvertes de neige mi-fondue, et le dessin de bande de roulement des pneus et leur état d'usure. On présente des calculs de performances pour un appareil de transport à réaction, en montrant l'influence de la couche de neige à demi fondue sur la piste sur la distance de décollage, et l'on indique aussi les effets des coefficients de freinage pneus/piste sur les distances de roulement à l'atterrissage. Ce rapport termine en donnant des indications des secteurs d'intérêt pour la recherche future.

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INVESTIGATIONS ON THE GROUND PERFORMANCE OF AIRCRAFT RELATING TO WET RUNWAY BRAKING AND SLUSH DRAG

Upshur T. Joyner, Walter B. Horne and Trafford J.W. Leland*

1 INTRODUCTION

The requirement that an airplane shall be able to take off and land under diverse weather conditions and operate satisfactorily on the ground while taxiing, turning, braking, and traversing rough runways and taxi strips, has a very significant influence on the design of the airplane. The extent of this influence on design was discussed by McBrearty¹ in 1957 at Copenhagen. An important element of the airplane landing gear which, to a great extent, influences the ability of the airplane to meet the above-stated requirements is the tire, because all ground forces are transmitted through the tire. It is necessary that the elastic characteristics of the tire be understood in order to be able to predict analytically the dynamic behavior of the airplane during ground operation, and because braking and side forces are dependent on the tire-to-runway friction characteristics, the variation of this friction with runway surface conditions and tire design must also be understood. The elastic properties of tires are fairly well covered in Reference 2, and numerous papers have been published giving values of tire-to-runway friction coefficient for various specific combinations of tire size, tire pressure, tread pattern, wheel load, forward speed, etc. It is often difficult, however, to find values of tire-to-runway friction coefficient for the particular combination of conditions of interest, especially if the interest is in large, heavily loaded tires operating at high speed, such as those on the modern jet transports and bombers, and to some extent on smaller military jet airplanes. Several investigations have been made in the United States recently to obtain more information on the operation of heavily loaded tires at high speed. The work involved braking tests on dry, wet, and slush-covered runways with tires having a variety of tread patterns, and measurement of the unbraked rolling resistance on the same runways. Part of this work was accomplished by NASA at the Langley Research Center, some was performed in flight tests by Boeing and American Airlines³, and some in another flight investigation performed jointly by the U.S. Federal Aviation Agency and NASA in 1961 (Ref. 4). This paper will deal mainly with a description of these recent investigations.

The presentation proceeds in the following sequence. First, a brief description of the track and its capabilities is given since many of the investigations to be described have been conducted at the NASA Landing Loads Track at the Langley Research Center, and this research track may not be familiar. Next, various factors affecting landing, take-off and ground handling are discussed, such as the runway surface conditions - whether dry, wet, or slush covered - and the tire tread pattern and its state of wear. Some interesting results on unbraked rolling resistance are shown. Also shown, because of the significance to the braking phenomenon, are results on the shift of vertical-load center of pressure in the footprint area during braking or rolling in water or slush. Comparison is made with respect to braking effectiveness between airplane flight-test results and Landing-Loads Track results. A summary is

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given of the joint FAA-NASA full-scale program conducted in 1961 to evaluate slush drag and braking problems on a current jet transport. Performance calculations are given for a typical jet transport to show the effect on landing runout distance of variations in tire-to-runway braking coefficient of friction that exists among the tire treads investigated; also indicated is the effect of runway slush on the take-off distance. The paper concludes with some mention of areas of interest for future research.

2. NASA LANDING LOADS TRACK

2.1 Description and Performance

The NASA Landing Loads Track can probably best be visualized by thinking of a hydrodynamic towing basin for ship or seaplane research work, and then imagining that the water basin is removed and a concrete runway is laid in its place. Figure 1 shows the schematic arrangement of the Landing Loads Track. The test carriage is indicated, and this carriage is catapulted to test speeds up to 125 knots by the hydraulic jet catapult indicated at the left (see Ref. 5). A water jet is expelled from a 7-inch-diameter nozzle under the influence of air at pressures up to 3260 lb/in² at a jet speed up to 660 ft/sec. This jet is received by a bucket on the back of the carriage, turned down and around through approximately 180°, and discharged rearward. The catapult develops a maximum thrust of as much as 350,000 lb and jet discharge exists for a period of up to 3 seconds. During these 3 seconds, the 100,000-pound carriage is accelerated to test speeds, and covers a distance of 300 to 400 feet during acceleration. Following acceleration, the carriage coasts freely for about 1200 feet before engaging the arresting gears, and during this phase the drop frame and landing-gear specimen are released from some predetermined height, and the test is accomplished. The carriage is stopped by the 5 arresting cables and 20 arresting engines in the 600 feet of track between arresting cable engagement and the storage shed. The Landing Loads Track has been in operation since 1955, and about 2000 test runs have been made with relatively trouble-free operation. Figure 2 shows the test carriage traveling down the test runway at a speed of about 80 knots. The landing gear being used is a four-wheel bogie. The investigation is concerned with the determination of slush drag.

2.2 Types of Research Performed

It may be inferred from the preceding description that landing research at the Landing Loads Track is subjected to fewer restrictions than have been inherent in some of the simpler test methods employed, e.g. tire rolling on the curved surface of a drum, tire dropping on an inclined plane, tire dropping on a flexible belt, tire rolling over the same small test surface repeatedly, etc. This is, in fact, the case. Following are descriptions of types of tests which have been performed that could not have been accomplished without a straightaway research facility.

(a) X-15 nose-gear shimmy research on dry concrete, wet concrete, and on concrete covered with loose sand. The X-15 nose gear was shown to be shimmy free, and the shimmy damper which had been provided was eliminated from the airplane. No shimmy has been encountered during airplane operation.

(b) Skid material research for application to reentry-type vehicles⁶. Skid-to-runway friction coefficient and wear rates were determined for a variety of materials in operation on concrete, asphalt, and on a dirt simulation of a dry lakebed.

(c) Tire-to-landing-surface coefficient of friction and landing-impact strength tests of a number of new type steel and aluminum portable runway surfacing materials⁷.

(d) Studies of impact loads developed on colliding with or running over various types of runway boundary lights and center-line lights⁸.

(e) Research relating to the effect of tire tread pattern on the braking effectiveness of a tire on a runway covered with water or slush⁹.

(f) Research into the retarding effect on tires of a deposit of slush on a runway¹⁰.

In addition to the above, research has been done on spin-up coefficient of friction^{11,12}, arresting cable runover loads¹², etc. One type of landing research for which there is a growing need, and which cannot be accomplished at the present Landing Loads Track, is research concerning the landing impact and runout stability of completely free, or unrestrained vehicles. This research is required in connection with the development of landing gears for various reentry vehicles. Studies are being made of ways of accomplishing this type of research.

3. TIRE-TO-RUNWAY BRAKING COEFFICIENTS

3.1 NASA Landing-Loads-Track Tests

It has been recognized for many years that the presence of various contaminating fluids on airport runways tends to impair the landing and take-off performance of aircraft. While this problem has been treated with some tolerance in the past, operational experience with high-performance military and civil jet aircraft has proven conclusively that these aircraft are much more severely affected by runway contaminants than were their propeller-drive predecessors. In order to explore more fully the effects of runway contaminants on braking effectiveness and rolling resistance of heavily loaded tires operating at high speed, an investigation was recently completed at the Landing Loads Track, using the test fixture shown schematically in Figure 3. This Figure shows how loads were obtained at the wheel axle, requiring only minor inertia corrections to derive the ground reactions. The test tire in all cases was a modern type VII aircraft tire, the brake assembly being that of a century-series jet fighter. During braking tests, brake pressure was controlled exclusively by the antiskid unit, thus simulating a pilot continuously riding the brakes. Close control of test conditions permitted the independent investigation of the effects of such parameters as forward velocity, tire tread pattern and tread wear, type of runway surface, and type of depth of runway contaminant. All tests were made with the tire rolling at zero yaw angle. Limited tests were run with the tandem gear arrangement shown in Figure 4, to investigate the path-clearing effects of the leading wheel. This wheel was pre-loaded with a hydraulic cylinder so that the vertical ground reaction would be the same for both wheels.

Some of the more important results of this investigation will be summarized in following sections. Most of the data are presented in terms of average braking friction coefficient, as shown schematically in Figure 5, rather than maximum braking friction coefficient, since the transient nature of the tire-slip phenomenon is such that operation by the pilot or antiskid system generally results in some overshooting or undershooting of the slip ratio required for maximum friction coefficient. The average friction coefficient developed between slip ratios of 0.1 and 0.5, Figure 5, was arbitrarily chosen in this Report as being more nearly representative of the friction coefficient attainable with present-day braking systems.

Effect of tire tread pattern - wet runway. Braking effectiveness on dry concrete proved to be relatively independent of forward velocity and tread pattern as shown by the upper curve in Figure 6. Braking on wet concrete, however, showed the expected serious degradation with increasing forward velocity, and a marked sensitivity to tread design. While the 9-groove rib-tread tire exhibited the best wet runway braking characteristics of all tires tested, it was not qualified as a high-speed tire, and could not be used in jet operations. The lower band in Figure 6 shows the friction coefficients developed by six smooth and dimple tread tires. The dimple tread tires were commercially available high-speed tires, while the smooth tread tires were furnished by a tire manufacturer expressly for this test. The smooth tires were new, and molded to full tread depth, but the tread pattern was omitted. These tires were tested both in the smooth condition and with various tread patterns cut into the tread. The dashed curve in Figure 6 shows the results of one of these modified treads, a five-circumferential-groove tire with two relatively wide grooves on either side of a narrow groove on the tire center line. The results shown in Figure 6 indicate that while braking performance may be improved through the use of proper tread design, the available friction coefficient at high forward speeds on wet runways may be only one-half to one-third of that available on dry runways, even with good tread designs. Footprints of the four different types of tread design are shown in Figure 7.

Effect of tire wear - wet runway. The extreme dependence of tire braking effectiveness on tread pattern would lead to the supposition that tire wear might be an important factor in wet runway braking. This is indeed the case and can be illustrated by examining the test results in a slightly different context, as in Figure 8, which shows test results for the same smooth tread tire, before (Fig.7(c)) and after (Fig.7(b)) modification. A four-groove modification, adding two grooves either side of the tire center line, nearly doubled the smooth tread friction coefficient at the higher speeds, while adding a fifth, narrow groove at the tire center line improved braking effectiveness still further. However, this Figure also shows the effects of tire wear, if it is assumed that the lower curve is for a tire which is worn to the point of having no tread at all. This is a valid assumption, as shown in Figure 9, where one of the test tires became exceedingly worn as a result of heavy braking action on dry concrete. As previously noted, the dry runway friction coefficient is unaffected by tire wear, but the wet runway braking effectiveness suffers a serious degradation, especially as the tire becomes 80 to 90 per cent worn. Therefore, it is apparent that, in order to obtain the best possible friction coefficient on wet runways, the tires must initially have an efficient tread design and must be replaced as the tread, through normal wear, approaches the smooth condition.

Effect of type of runway surface - wet runway. In order to investigate the effect of different runway surfaces, a strip of asphalt paving was laid parallel to the concrete test runway. Half of this asphalt had a smooth sand finish, the other half a rough aggregate finish. A comparison of braking friction on one wet concrete and two asphalt surfaces is shown in Figure 10. Little difference in friction coefficient was noted between the two types of asphalt surface, but the average coefficient tended to be somewhat higher on the wet asphalt than on the wet concrete, especially at the lower forward velocities.

Other runway surface contaminants. While water is the most commonly encountered runway surface contaminant, other contaminants also have a pronounced effect on airplane braking effectiveness. Fire extinguishing foam, when used to coat the runway surface in the event of an emergency landing, reduces the braking friction coefficient of a dry concrete runway to about the level of wet concrete as shown in Figure 10. In this case the blanket of foam was from 2 to 5 inches thick, and consisted of both organic and detergent type foam in two discrete strips. No difference in available friction coefficient is discernible between the two types of foam. Also shown in Figure 10 is the effect of contaminating an asphalt runway with a mixture of JP-4 jet fuel and water. To simulate this condition for test purposes, the asphalt strip was first coated lightly with JP-4, which was allowed to stand until most of the fuel had either evaporated or been absorbed by the surface. The asphalt was then lightly sprayed with water to simulate the beginning of a rain shower and, as shown in Figure 10, this combination of contaminants further depressed the available friction coefficient.

Of all the runway contaminants encountered during routine operations, the presence of slush on the runway probably has the most severe effect on aircraft performance, not only through degradation of braking effectiveness, but through reduction of take-off performance due to slush drag. The problems of slush drag acting on a freely rolling tire will be discussed in a later section of this Report. To demonstrate the degradation of braking effectiveness due to slush, Figure 11 shows a comparison of friction coefficients developed on a dry concrete runway (curve E), on a wet concrete runway (curve A), and on a concrete runway covered with $1\frac{1}{2}$ inches of slush (curve B). Curve B is the apparent friction coefficient developed by the tire braking in slush, which shows a tendency to increase with increasing forward velocity. An explanation for this phenomenon can be found if the drag due to slush displacement by the tire is considered, which is shown in Figure 11 by curve C, calculated from free-rolling data. If this drag due to slush is subtracted from the apparent friction coefficient, the actual tire-to-ground friction coefficient is obtained as curve D in Figure 11, and is seen to result in only about half of the wet runway, or about one-fourth of the dry runway, braking effectiveness.

3.2 Airplane Flight Tests

Many uncertainties existed in attempting to expand the Landing Loads Track single-wheel braking test results to predictions of ground performance for particular large aircraft. These included the effects of different tire sizes, types, and construction, tire pressure and vertical load, number of wheels, wheel location and spacing, forward speeds higher than those of the single-wheel tests, and particular antiskid system performance. To resolve these uncertainties, NASA welcomed the opportunity to

correlate Landing Loads Track results with flight-test data. Two such correlations that were made will be discussed in the following paragraphs, wherein a comparison is made between track single-wheel test results and results for three different types of modern jet-powered transport aircraft.

Boeing-American Airlines tests - 707 airplane. These tests were a cooperative effort by Boeing Airplane Company and American Airlines, whose purpose was to determine the effect of tire tread design on airplane braking coefficients on wet and dry runway surfaces, and to determine the validity of NASA track tests for application to full-scale jet transports. The wet runway tests were run at Boeing Field, Seattle, Washington, during a time when the runway was continuously wet following rain showers, as opposed to the artificial wetness used in the Landing Loads Track tests. Airplane braking coefficients were obtained from basic phototheodolite tracking data, and since they were derived from a decelerating force, are expressed as overall, or effective, friction coefficients in Figure 12. Included for comparison in this Figure are track single-wheel test results for the same general type of runway surface and tire tread design. It is felt that while some of the difference in results of the aircraft tests and track tests is because of the difference in definition of average and effective friction coefficients, at least part of this difference is probably due to the 'squeegie', or pathclearing action of the leading wheels of the four-wheel bogie gear with which the test aircraft were equipped. An effect similar to this was noted in limited tests at the Landing Loads Track, where a freely rolling tire of the same type and size as the test tire, and having the same vertical loading, was placed ahead of the test tire (see Figure 4) during braking runs in water and in slush. However, despite the generally higher friction coefficients developed by the airplane with non-rib tread tires, the same trends are noted as those established by the track tests, that is a sharp decrease in friction coefficient with increasing forward velocity, and a very definite sensitivity to tire tread design.

FAA-NASA tests - 880M airplane. A joint test program was undertaken by FAA-NASA to provide accurate flight-test data as a check on certain of the Landing Loads Track single-wheel test results. The program was to investigate two distinct areas, the first area being aircraft behavior while braking under adverse runway conditions, and the second area, which will be discussed in a later section of this paper, being an evaluation of the retarding effects on take-off performance due to the presence of slush on the runway.

The test airplane, an FAA Convair 880M, carried an onboard instrument package supplied by NASA to measure and record aircraft acceleration, attitude, airspeed, and aircraft landing wheel rotational speed. In addition, phototheodolite tracking, radar tracking, and tape switches on the runway surface were used to provide basic position-time data. The aircraft was equipped with rib tread tires maintained in good condition, and all braking tests were made with the aircraft in aborted take-off configuration, engines at idle thrust, and antiskid system in full control of brake modulation with no pilot inputs. Test runs were made on dry and wet concrete runway surfaces, and on foam- and slush-covered surfaces. Aircraft braking coefficients are shown in Figure 13 for the dry, wet, and slush-covered runway conditions, and comparison with Figure 11 indicates reasonably good agreement between the single-wheel braking and aircraft braking results. It will be noted from Figure 13 that, at the higher test velocities, wet runway braking effectiveness is only about half that

experienced on a dry runway, and in the presence of slush, braking effectiveness drops to only about one-fourth the dry runway equivalent.

During the course of the test program, several test runs were made on a foam-covered runway with the results shown in Figure 14. A comparison is made in this Figure of the test results on wet concrete as well as foam, since some consideration had been given to the use of foam to make a standard reproducible low-friction-coefficient surface for certification and testing purposes. The agreement indicated in Figure 14 indicates that this method holds some promise and would bear further investigation.

3.3 Effect on Stopping Distance for a Typical Jet Transport

Some results from the single-wheel braking investigation have been used to predict the effect of tire tread pattern on the wet runway stopping distance for a typical four-engine jet transport. These predictions are shown in Figure 15 for three of the tires tested. All stopping distances are based on the distance traversed after touchdown of the aircraft, which occurs at 140 knots. The solid curves in Figure 15 are the dry runway stopping distances derived from data supplied by the aircraft manufacturer. In Figure 15(a), thrust reversers are assumed to operate between 120 knots and 75 knots, and it can be seen that the wet runway stopping distance is not materially greater than the dry runway stopping distance for the two rib tread tires, but another 1500 feet of runway are required to stop if smooth tires are used. In Figure 15(b) it is assumed that thrust reversing is not available, and in this case smooth tires braking on wet concrete will require nearly 2300 feet more than the equivalent dry runway stopping distance.

4. RETARDATION FORCES ON A FREELY ROLLING AIRCRAFT TIRE

4.1 NASA Landing-Loads-Track Tests

Concurrent with the single-wheel braking tests described previously, an investigation was made of the drag forces developed on a tire while rolling unbraked on dry, water-covered, and slush-covered runway surfaces. The purpose of the investigation was to explore the effects of such parameters as forward velocity, type and depth of runway fluid, and the path-clearing ability of the front wheel in a tandem wheel arrangement, with the hope that a usable theory could be developed to predict the effects of these parameters on the take-off performance of modern aircraft. The same test fixture described previously, Figures 3 and 4, was used, the only difference being that no brakes were used in this investigation.

General considerations. The forces acting on an unbraked, loaded tire are shown schematically in Figure 16 for various rolling conditions. The static tire, Figure 16(a), is acted on only by the vertical load on the tire, and probably has a symmetrical pressure distribution in the footprint region, as shown, with the center of pressure located under the wheel axle center line. An unbraked tire rolling at constant velocity on a dry runway, Figure 16(b), has acting, in addition to vertical load, a drag load caused by rolling resistance due to bearing friction, tire hysteresis, and other effects. This drag load causes a spin-up moment about the tire

which, for constant angular velocity, must be countered by a shift of the vertical-load reaction to a position ahead of the axle center line. This shift of the center of pressure probably distorts the pressure distribution in the tire footprint region in some manner as indicated in Figure 16(b). The situation for an unbraked tire rolling on a fluid-covered runway is shown in Figure 16(c). Here the drag produced by the tire displacing fluid out of its path acts in concert with the rolling resistance to produce a larger spin-up moment, which must be opposed by the center of pressure moving still farther ahead of the axle center line. It is supposed that, as the fluid penetrates the footprint region, a hydrodynamic lift force is created, which acts to spin down the tire. As the forward speed of the tire is increased, a wedge of fluid probably penetrates farther and farther into the footprint region, the hydrodynamic lift force becomes progressively greater and, at some high forward speed, complete separation between the tire and runway should occur, a condition called tire hydroplaning. Since at this time the tire is supported by the runway fluid, the tire frictional spin-up moment is greatly reduced, and the tire will spin down to a stop. Some preliminary experimental data supporting these conclusions will be presented in the following sections.

Rolling resistance of a tire on a dry runway. The variation of rolling resistance coefficient, or the ratio of ground drag load to vertical load, with forward velocity, and the calculated variation of center-of-pressure movement with forward velocity is shown in Figure 17 for a tire rolling freely on dry concrete. The rolling resistance (Fig. 17(a)) is seen to increase with increasing forward velocity as previous work in this area has indicated, although the values obtained in this test are somewhat higher than expected. Figure 17(b) shows the calculated tendency for the center of pressure to move farther ahead of the wheel axle center line to counteract the increasing rolling resistance, as indicated in Figure 16(b).

Retardation forces on water-covered runways. In this investigation, a test trough was constructed on the runway surface using a system of dams and dikes, and this trough was filled with water to the desired level for the test. The water depth was kept as uniform as possible within limits imposed by existing wind conditions and runway gradients. The variation of fluid displacement drag and center-of-pressure movement with forward velocity for two water depths are shown in Figure 18. The scatter of the data is felt to be due primarily to unavoidable variations in water depth, but clearly the trend is for the drag forces to increase sharply with forward velocity and with fluid depth. The solid curves in Figure 18 are predictions based on an equation developed in Reference 10, which assumed that the drag force was proportional to fluid depth and density and to the square of the forward velocity. Reasonably good agreement is indicated between experimental and calculated values for the fluid depths noted. Also in Figure 18, a large center-of-pressure movement is calculated as fluid drag forces increase, which supports the ideas considered in Figure 16.

Retardation forces on slush-covered runways. On modern, adequately drained runways, standing water of the depths previously mentioned may never be encountered. Accumulations of slush, however, may easily reach 1 or 2 inches or more, and slush depths of this magnitude can make aircraft operation extremely hazardous. The retardation force developed on a single wheel rolling through 2 inches of slush is shown in Figure 19, where drag due to slush is plotted as a function of forward velocity. The solid curve in the Figure is the predicted slush drag based on the

equation in Reference 10 which assumes drag to be proportional to fluid density and to the square of the forward velocity. A drag coefficient of 0.75, used in this case, gives relatively good agreement with experimental data. It should be emphasized that the slush drag data shown in Figure 19 is slush displacement drag only, and that Reference 10 predicts slush drag on this basis, with no other effects of slush being considered. The solid point near the bottom of Figure 19 is the drag experienced by the rear wheel in the tandem wheel arrangement shown in Figure 4. This reduced drag on the rear wheel is a result of the path-clearing action of the leading wheel, and was found experimentally to be only about one-tenth the drag experienced by a leading wheel.

To compare directly the drag experienced by a single wheel rolling on dry, water-covered, and slush-covered runways, Figure 20 shows a time history of a typical test run through slush and water troughs on a concrete runway. At time zero the tire is rolling freely on dry concrete, at constant velocity, with low drag load and small forward shift of center of pressure. As shallow water is encountered, time 0.4 approximately, the drag load increases, the center of pressure shifts farther forward, and the tire starts to spin down. As 2 inches of slush is encountered, the drag load increases sharply, the center of pressure shifts very far ahead of the axle, and the tire continues to spin down. Later tests confirmed that with sufficient slush trough length the tire will come to a complete stop and remain stopped until the forward velocity drops below that velocity required for tire hydroplaning, at which time the tire will spin up again.

Continuing on with the time history in Figure 20, at the end of the slush trough the tire again encounters a dry runway, and immediately spins up, causing a large spin-up drag load. As the tire enters the deep water trough at time 2.3, drag load again increases, center of pressure shifts forward, and tire spin-down begins, since the forward speed is still in excess of that required for tire hydroplaning.

4.2 FAA-NASA Airplane Tests - 880M Airplane

Many unresolved questions arose as a result of the single-wheel slush-drag test just described, particularly regarding the effects of tire size and wheel spacing on multiple-wheel landing gears, and further retardation forces caused by slush spray impingement on aircraft surfaces and slush spray interference between wheels in a bogie, and between bogie pairs. Concurrent with the joint FAA-NASA aircraft braking tests described in a previous section, a series of slush-drag tests was made to investigate these and other effects on the test airplane, a Convair 880M. To evaluate the drag due to slush, the airplane was first accelerated to the desired test velocity on a dry runway, the engines brought to idle thrust, and the airplane allowed to coast freely through the slush test bed. Upon exit from the bed, there remained 5000 feet of dry runway to effect a safe stop, or to take off at the pilot's discretion. The slush test bed in most cases was 1000 feet long and 50 feet wide, although a longer bed was used for an actual take-off through slush which was made to validate the deceleration data which formed the bulk of the investigation.

The results of the deceleration tests are summarized in Figure 21. Since it proved impossible to hold the depth of the slush constant, all slush-drag data have been normalized to a standard 1-inch depth to permit direct comparison of all test data. The dashed curve in the Figure is the predicted slush drag based on the single-wheel

tests, using the method of Reference 10. In the velocity region below 120 knots, the airplane encountered about twice the drag predicted on the basis of slush displacement only, a clear indication that slush impingement drag and slush interference drag, which were not present in the single-wheel tests, make a major contribution to the total retardation force. Above 120 knots, slush drag is seen to increase with increasing forward velocity, an effect attributed to tire hydroplaning with the tire riding higher in the slush bed. This was confirmed by examinations of wheel angular velocity measurements, which showed wheel spin-down and even wheel stoppage in this region. Motion pictures also showed a change in spray patterns with increasing velocity, the tendency being for the slush spray to become flatter, reducing impingement drag, as the tire rides up out of the slush surface during hydroplaning. The results shown in Figure 21 indicate that conservative predictions of take-off performance in slush cannot be made on the basis of slush displacement alone, and that further tests are needed to determine whether the slush retardation forces experienced by the test airplane can be extended to all aircraft, or if each aircraft type must be treated independently owing to aircraft configuration, wheel location, etc.

The effects of slush on total take-off distance are shown in Figure 22 for the test airplane, wherein predictions for $\frac{1}{2}$ inch and 1 inch of slush, based both on the method of Reference 10 and on the joint FAA-NASA aircraft test results, are compared with the dry runway take-off distance. It can be seen from this Figure that the presence of more than about $\frac{1}{2}$ inch of slush on the runway will severely compromise safety requirements in the event of an aborted take-off, especially if the greatly decreased braking effectiveness due to slush, Figure 13, is considered. For the past two winters the FAA in the U.S. has prohibited operation of jet transports in slush deeper than $\frac{1}{2}$ inch.

5. CONCLUDING STATEMENTS

5.1 Conclusions from Work Described

The following conclusions may be reached on the basis of preceding discussions:

Braking tests at the Landing Loads Track indicated that tread design is a major factor in wet runway braking performance, with a multi-circumferential groove tire giving the maximum wet runway braking effectiveness of all tread designs tested. Clearly demonstrated also was the adverse effect that runway contaminants may have on braking effectiveness, reducing available friction coefficient by as much as one-third at higher velocities.

Aircraft tests generally confirmed the findings of the track tests, giving confidence in the test facility and procedures.

Retardation forces acting on a single wheel rolling through slush or water were found to increase parabolically with increasing forward velocity, based on fluid displacement drag only. Preliminary calculations based on the results of these tests indicated extreme increases in take-off distance for large depths of slush or water, and caused the FAA to issue the 'half-inch rule', which prohibited jet transport take-offs through slush depths greater than $\frac{1}{2}$ inch. Subsequent aircraft tests gave

no reason to change this half-inch rule, and indicated that the airplane experienced about twice the drag to be expected from slush displacement alone, emphasizing the importance of slush impingement on aircraft surfaces.

5.2 Areas of Interest for Future Research

An investigation is currently in progress at the Landing Loads Track to determine in more detail the effects of slush and water retardation forces on the unbraked dual-tandem bogie gear shown in Figure 2. The objectives of this investigation are to measure the total retardation force on the bogie gear due to the presence of slush, and if possible to isolate and evaluate the separate effects of slush impingement drag and slush interference drag, and how these effects may be reduced through gear geometry, flap location, etc. Also, more will be learned of the tire hydroplaning phenomenon, through the use of the runway surface pressure gages.

Results of the braking investigation which have been briefly described in this Report seem to indicate that still further improvements in wet runway braking effectiveness are needed, but that further studies of different tread designs would result in only small additional gains. Previous related work^{7, 12} has indicated that perhaps greater gains in the future may result from a modification of the runway surface rather than the tire surface. Currently available are several different types of runway surface additives as well as many methods of modifying the runway surface through scarification or other means, all of which are intended to improve wet runway braking effectiveness. In order to determine which method or combination of methods is most applicable, it is necessary to know both costs and friction properties. Costs are readily available, but friction properties need to be determined.

All braking tests and free-rolling tests described in this Report have been under conditions of straight-ahead rolling with no yaw. Since yawed rolling conditions are frequently encountered in aircraft operations, an investigation is needed to study the high-speed yawed rolling characteristics of an aircraft tire. Such an investigation might utilize the single-wheel test fixture in Figure 3, which may be rotated almost 90° in either direction from zero yaw, to duplicate many of the test conditions cited in this Report, both in free-rolling and in braking, so that the effects of yawed rolling may be isolated.

Further inquiry seems desirable into conditions in the contact area of a tire at sub-hydroplaning and hydroplaning velocities. It is hoped that high-speed photographs will be made of a tire rolling over a glass plate, and more extensive runway pressure measurements obtained, to determine with some accuracy the shape of the tire footprint pressure distribution, and to measure directly the shift in footprint center of pressure with changes in forward speed.

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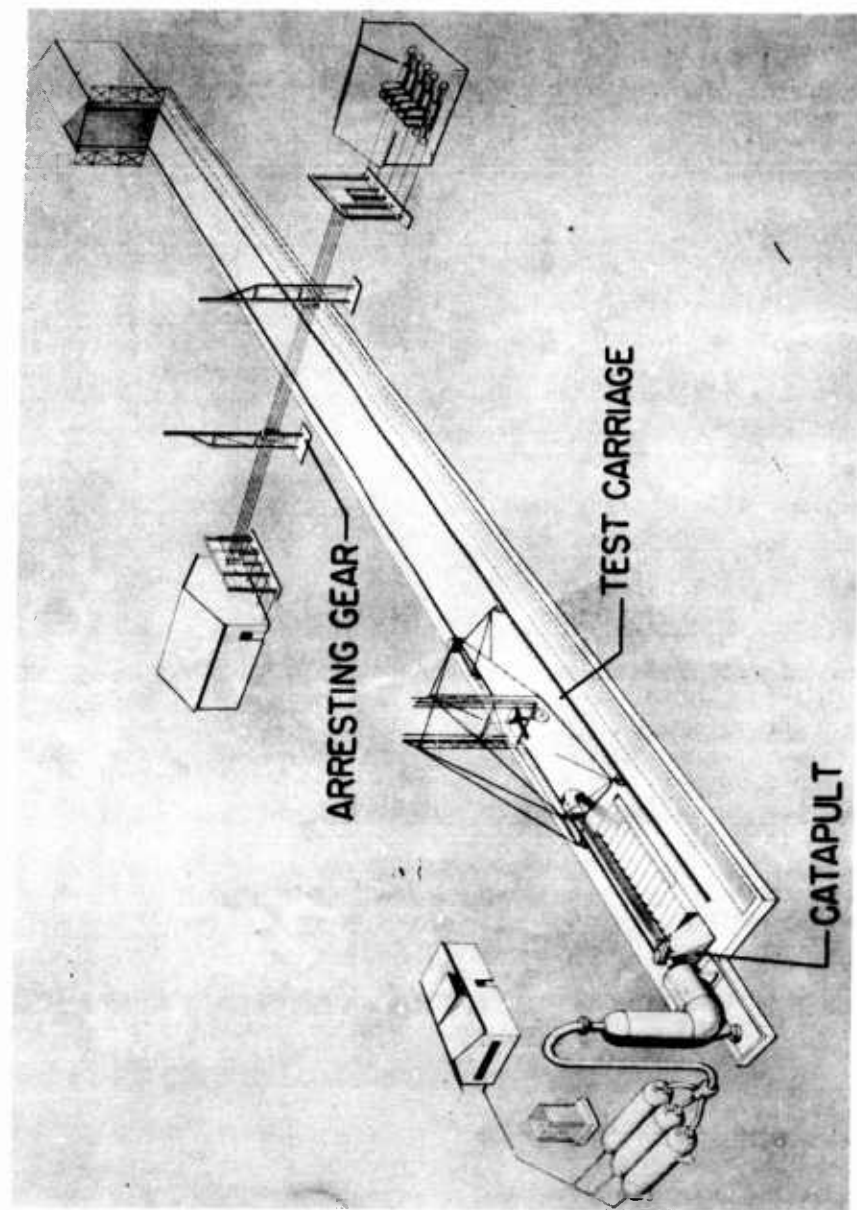


Fig. 1 Schematic of Landing Loads Track

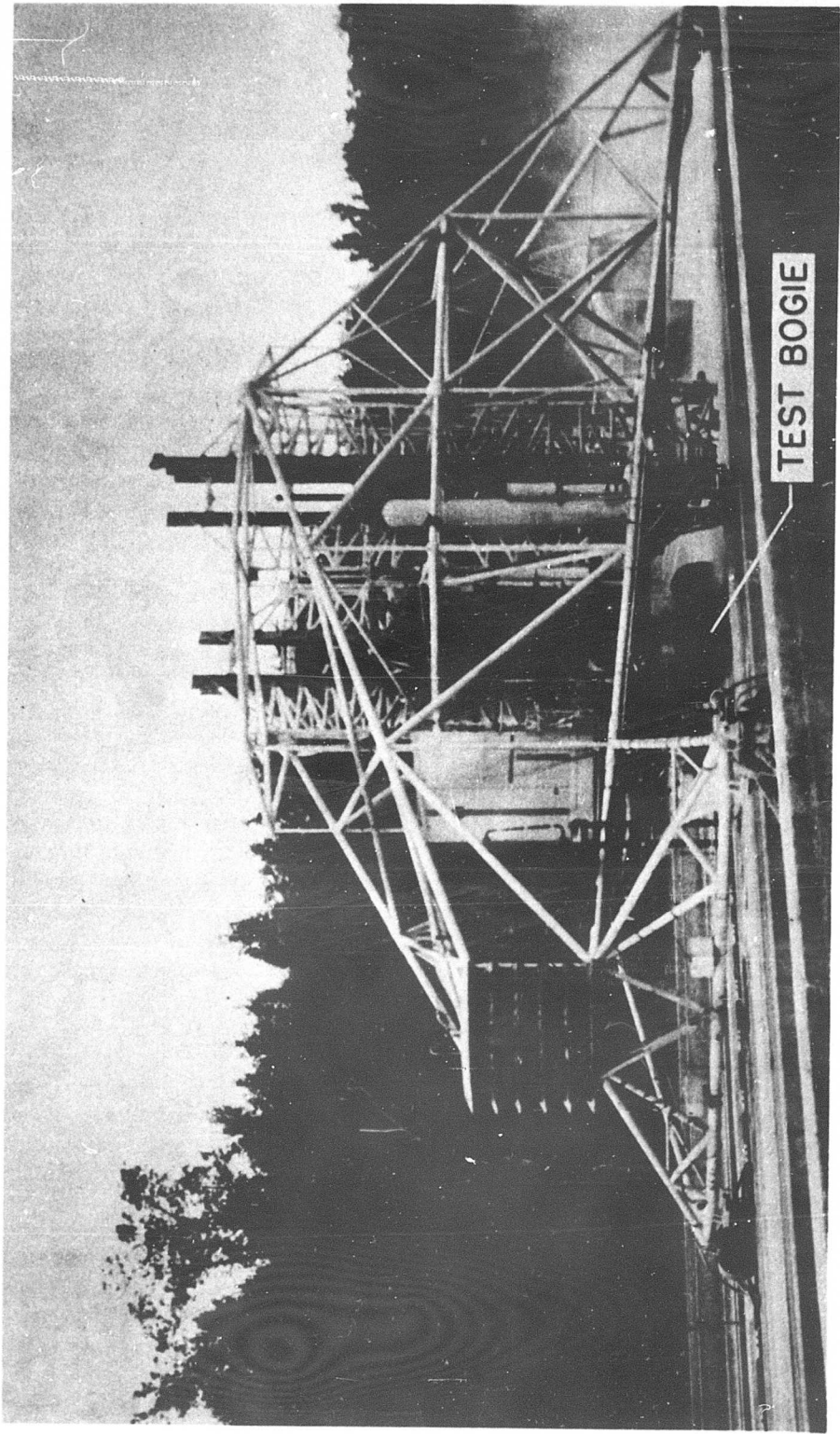


Fig. 2 Test carriage of Landing Loads Track

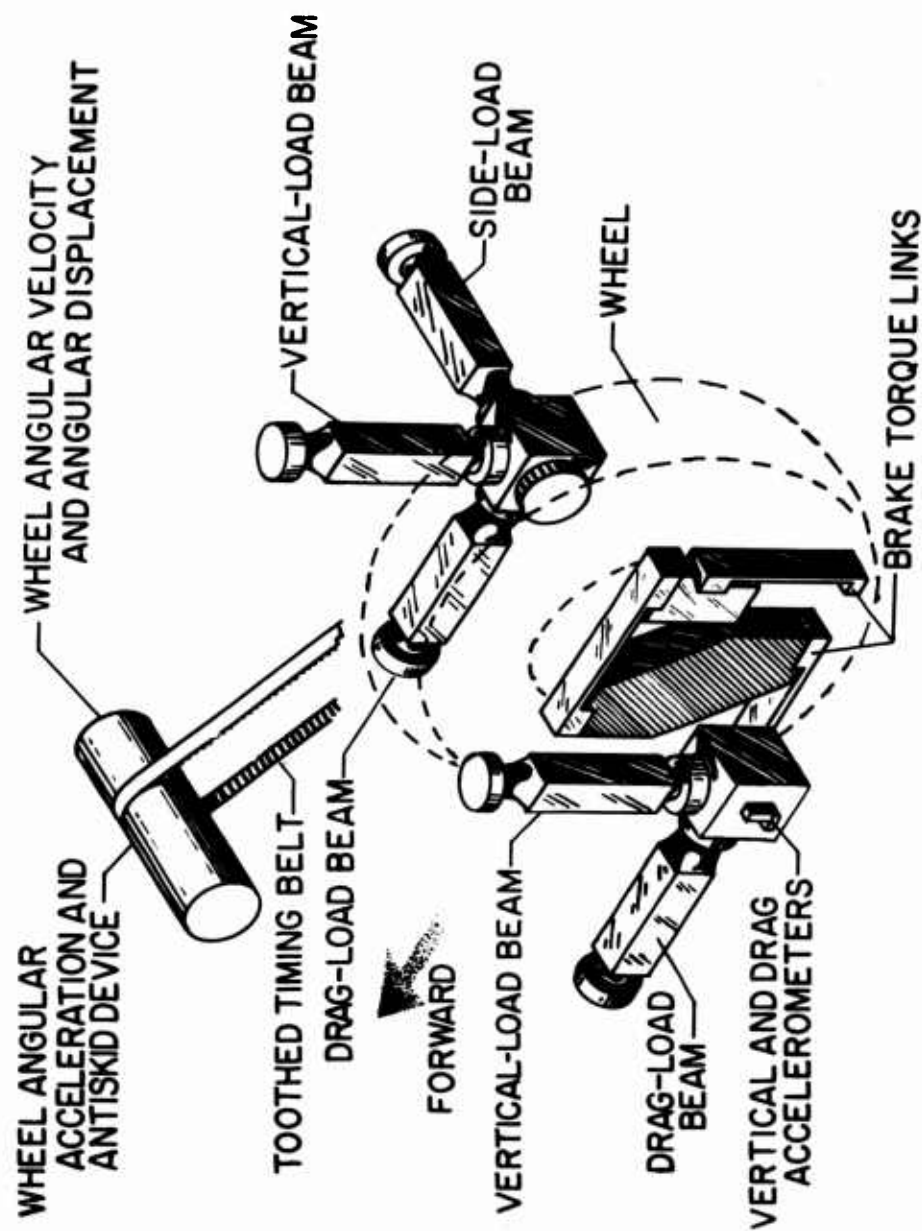


Fig. 3 Schematic of single wheel test fixture

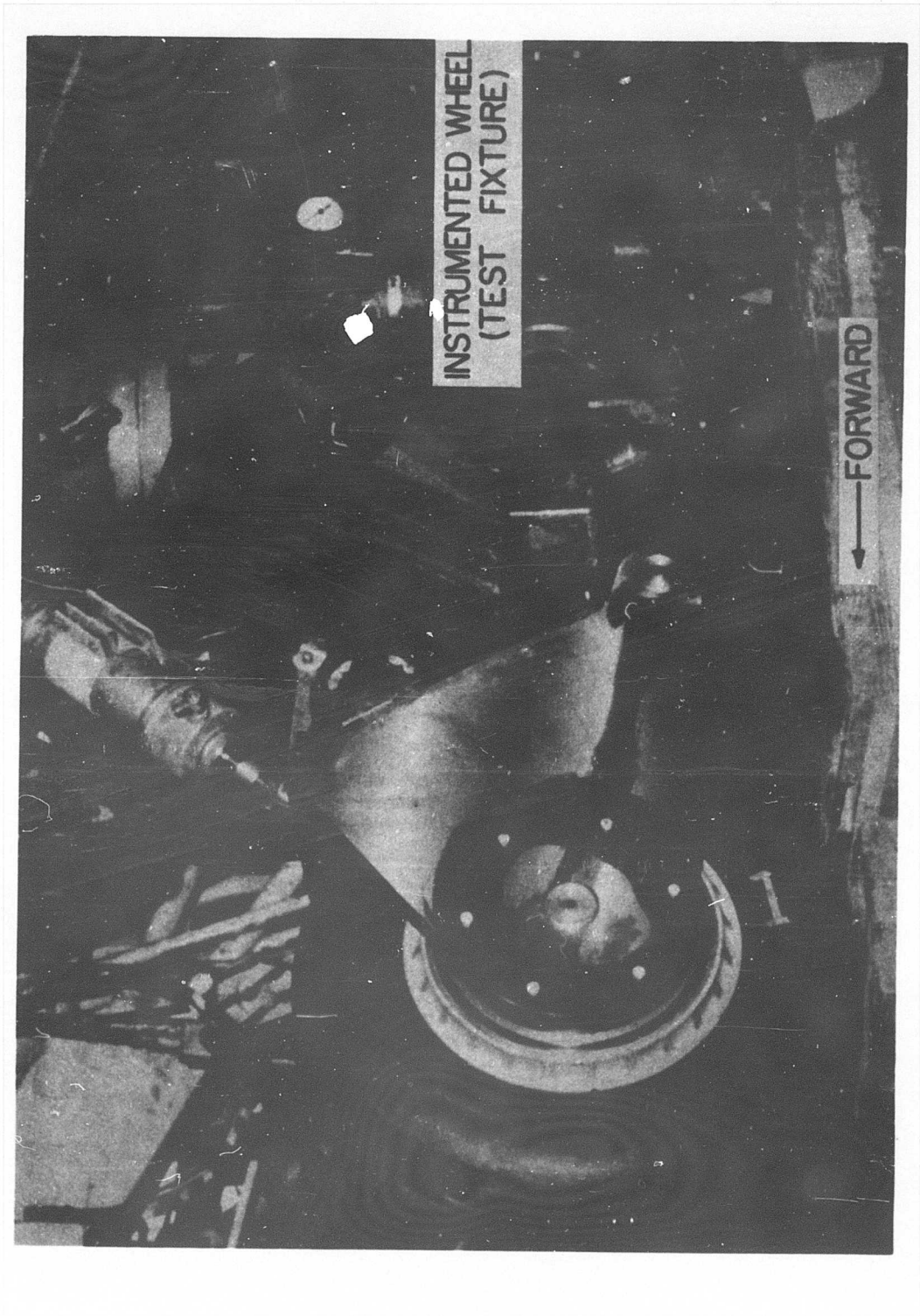


Fig. 4 Tandem wheel setup at Landing Loads Track

DRY RUNWAY

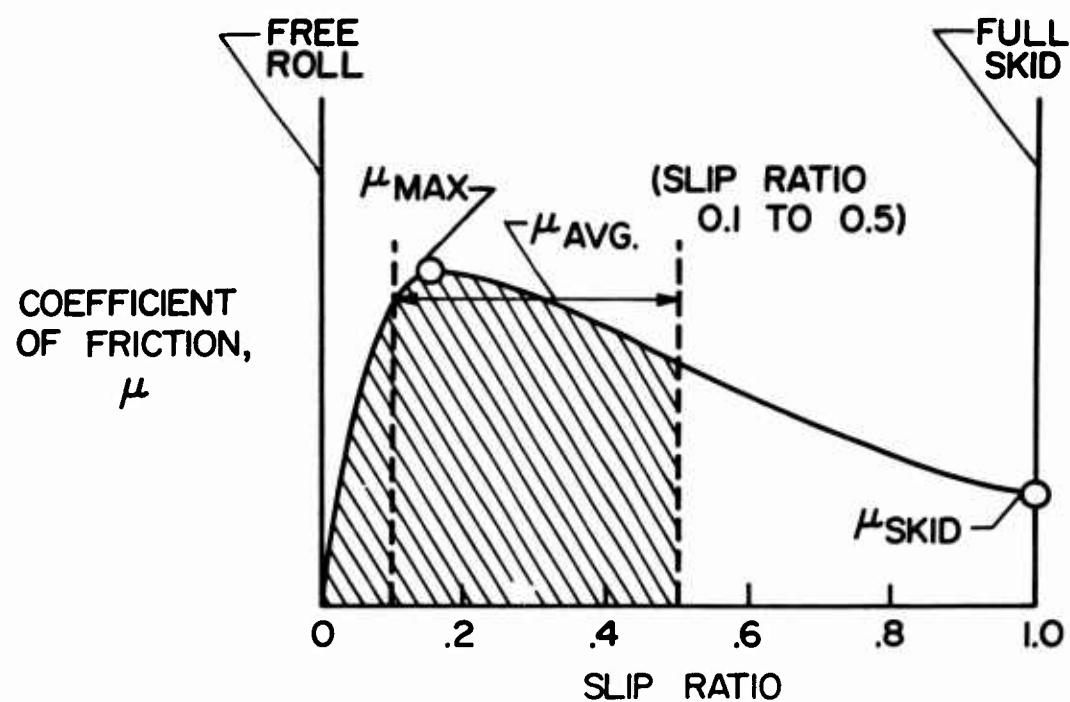


Fig. 5 Schematic variation of friction coefficient with slip ratio

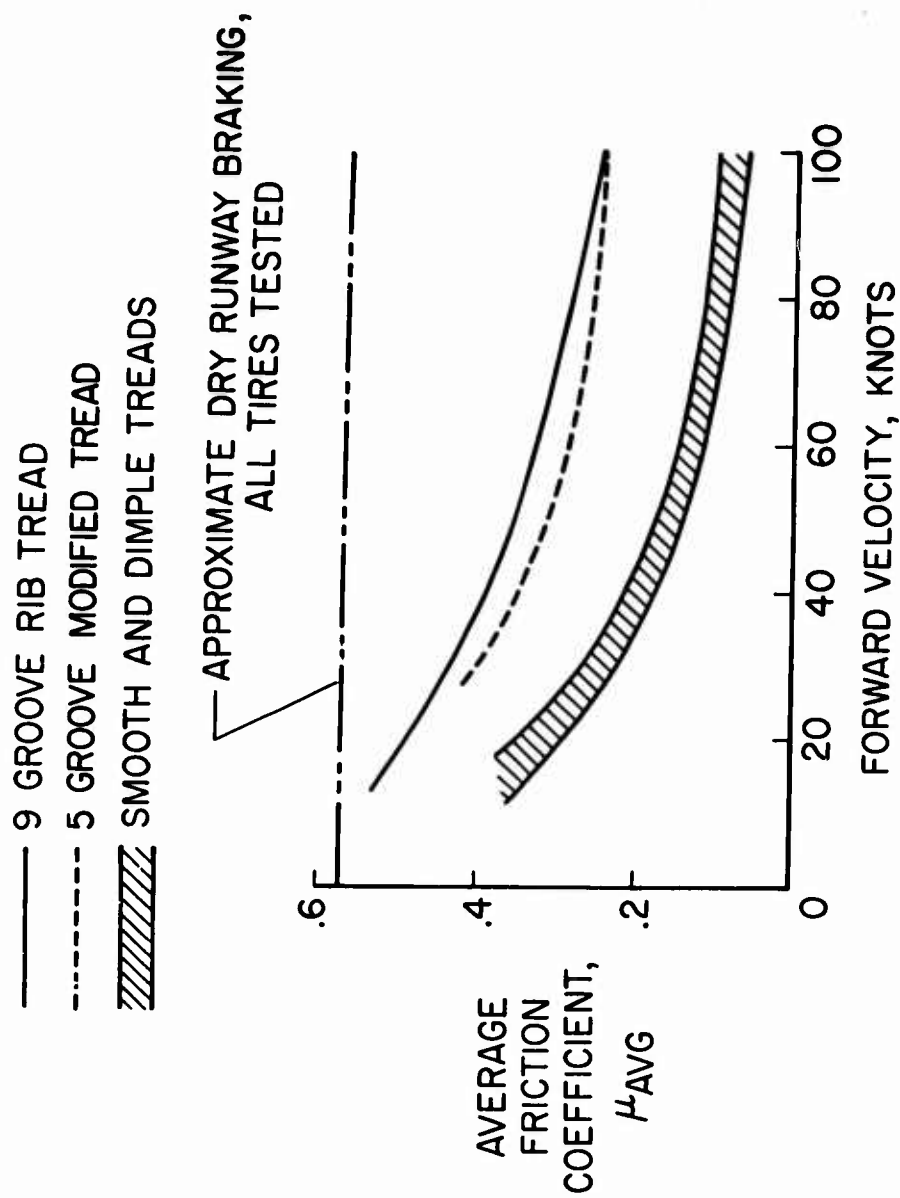


Fig. 6 Effect of tire tread design on wet concrete runway braking

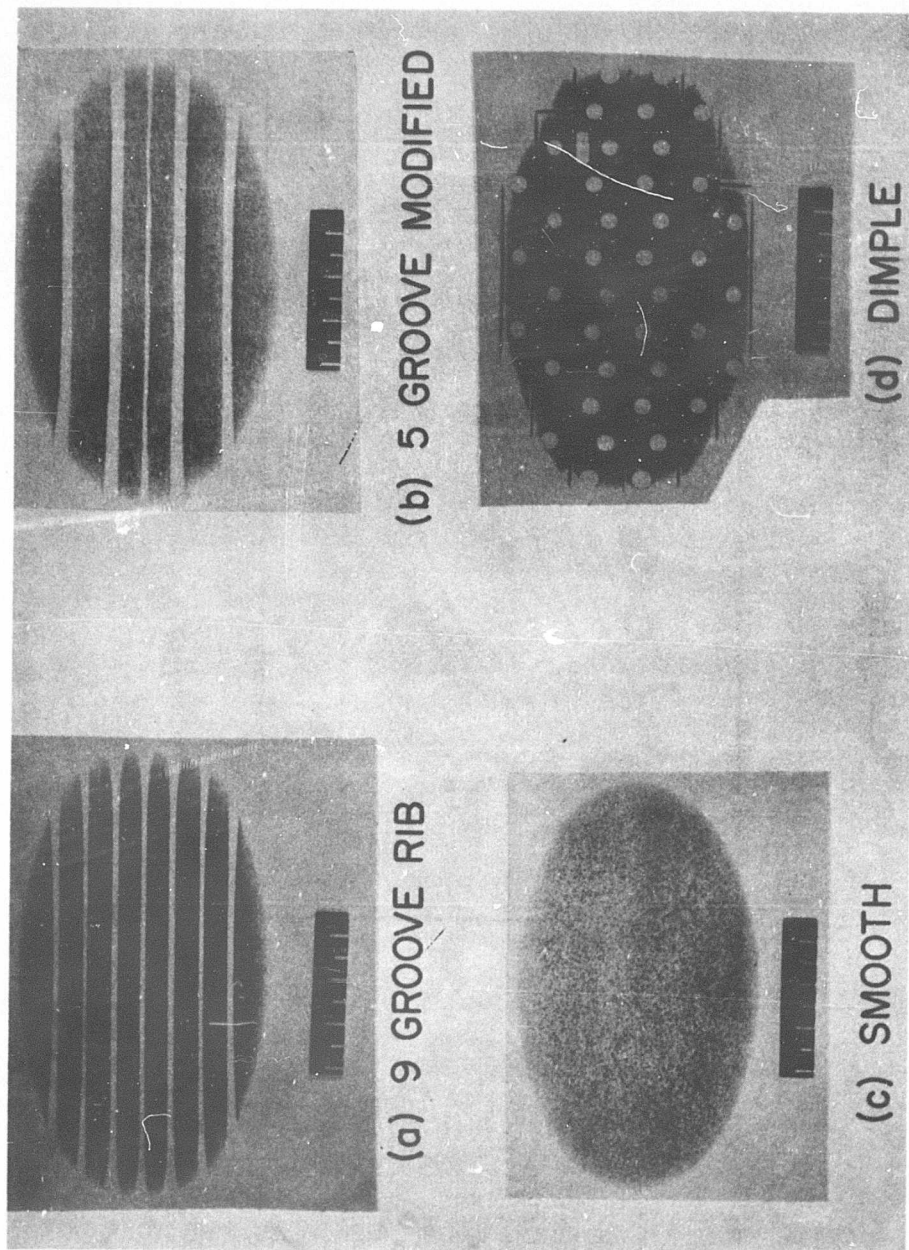


Fig. 7 Footprints of four of the tires tested

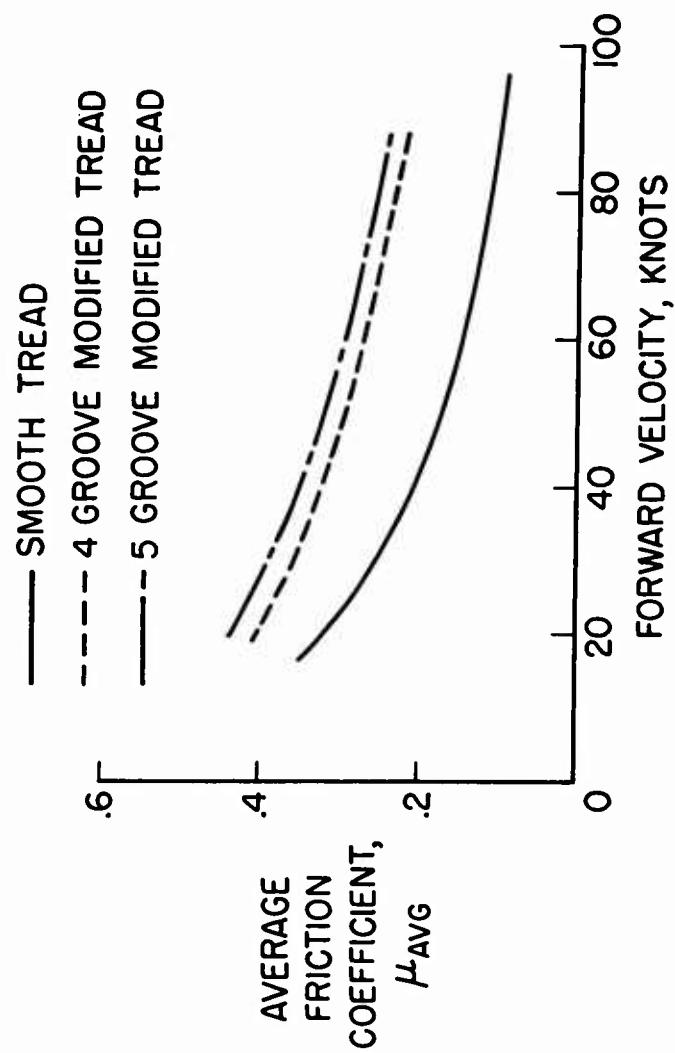


Fig.8 Effect of tire tread design on tread wear on wet concrete runway braking

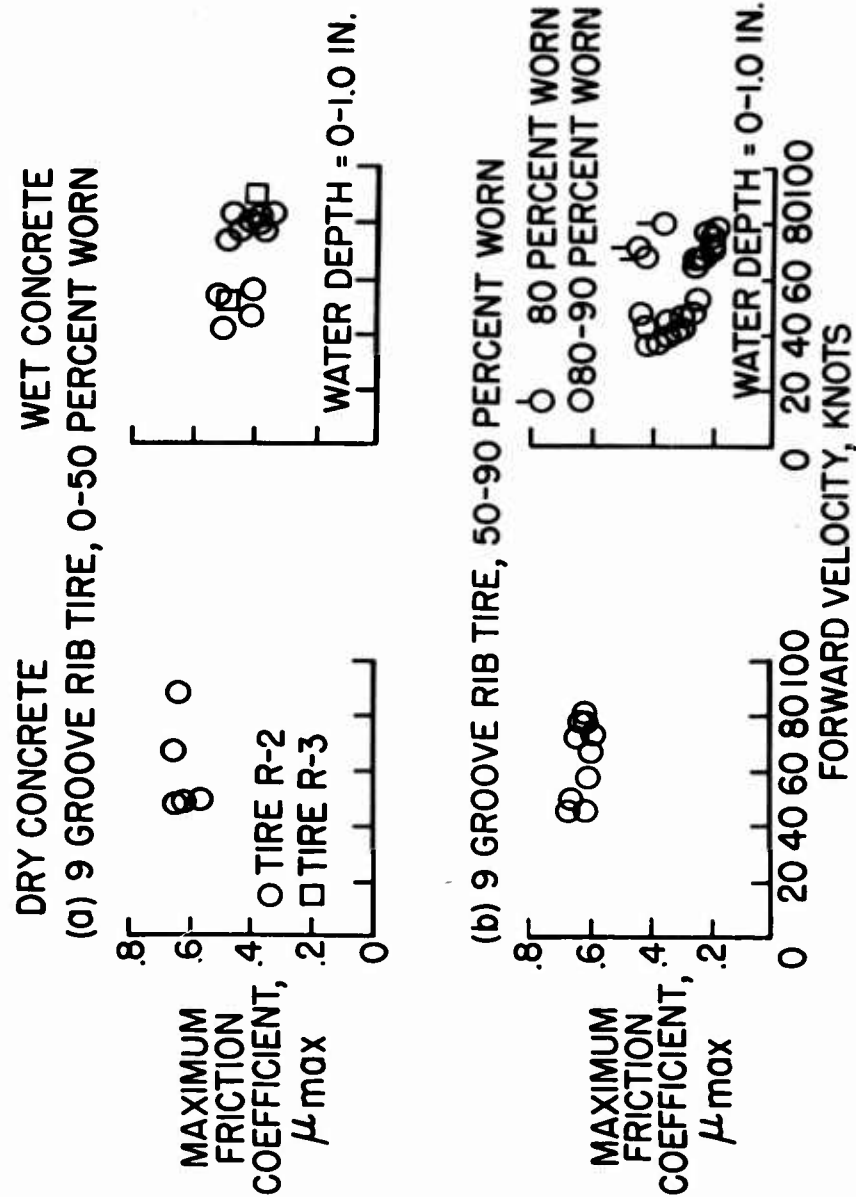


Fig. 9 Effect of tread wear

5 GROOVE MODIFIED TREAD TIRE

- ORGANIC FOAM ON CONCRETE
- DETERGENT FOAM ON CONCRETE
- ◇ JP-4 JET FUEL & WATER ON ASPHALT

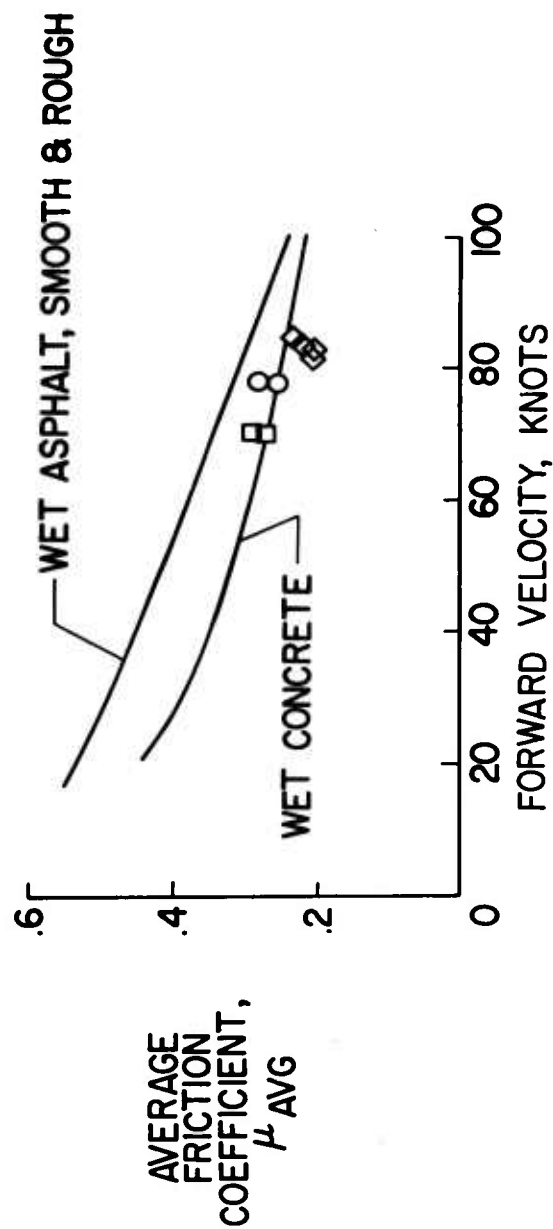


Fig. 10 Effect of type of runway surface and certain contaminants

5 GROOVE MODIFIED TREAD TIRE

- A — WET CONCRETE
- B ---- SLUSH, 1.5 INCH DEPTH
- C ---- SLUSH DRAG (CALCULATED)
- D ---- BRAKE
- E ---- DRY RUNWAY (APPROX.)

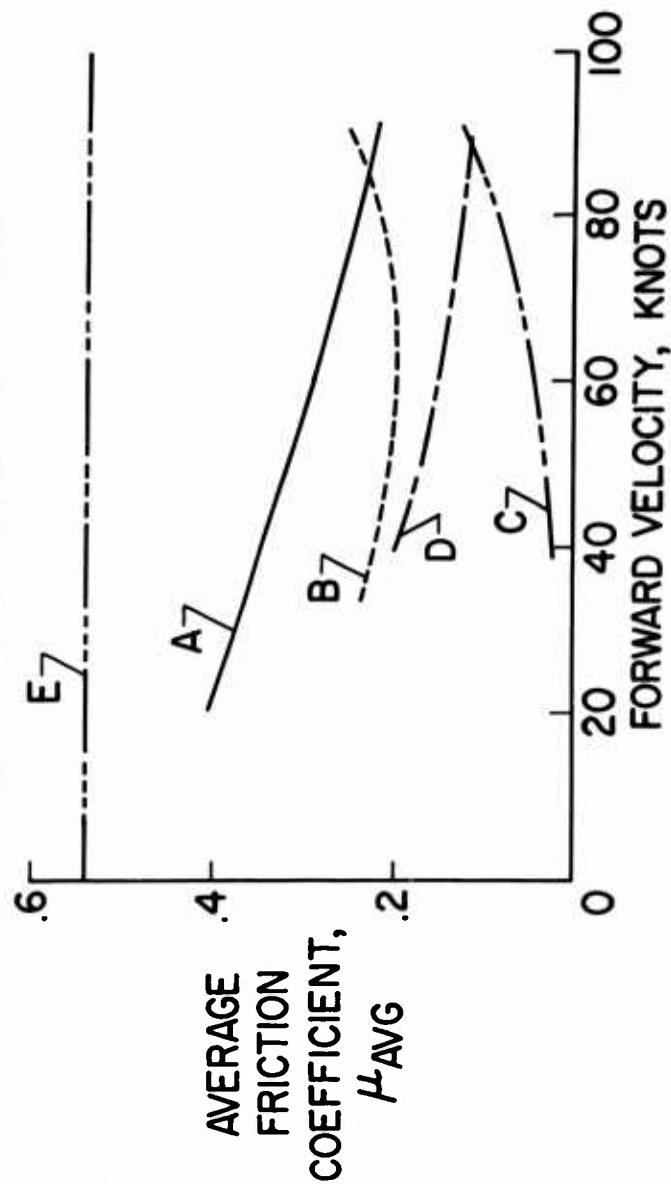


Fig. 11 Effect of slush on single-wheel braking

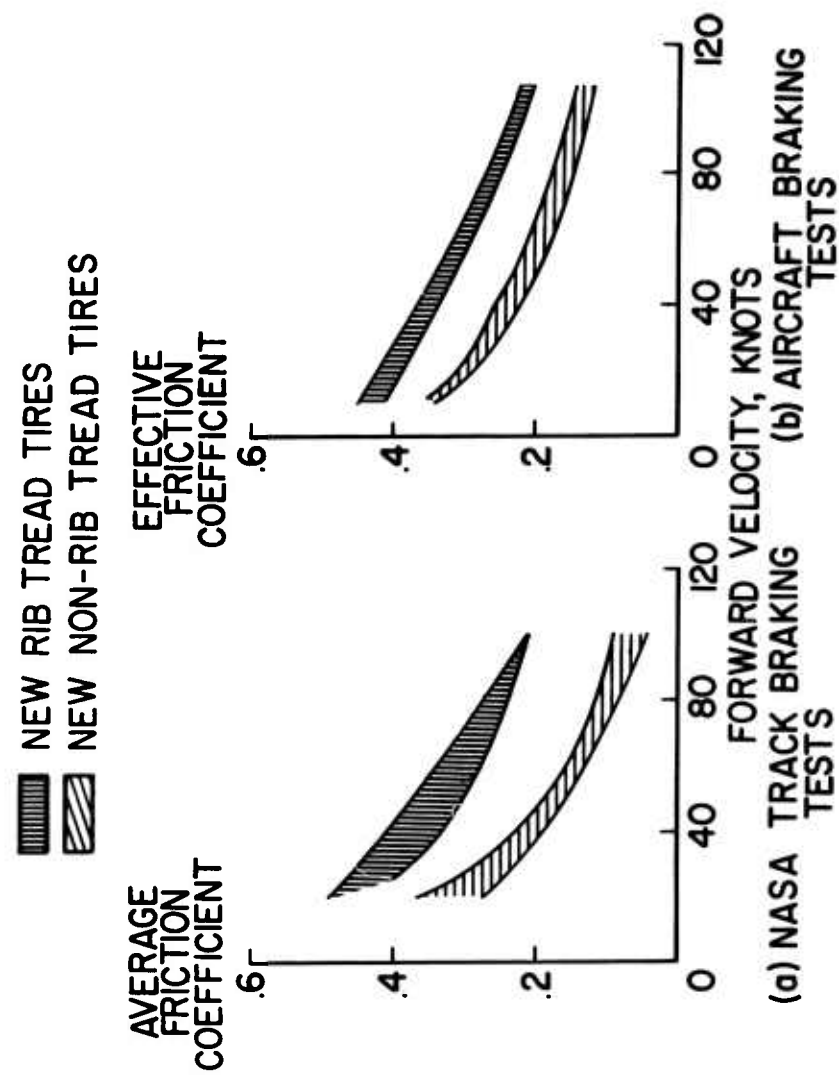


Fig. 12 Comparison of track and aircraft braking tests on concrete runways

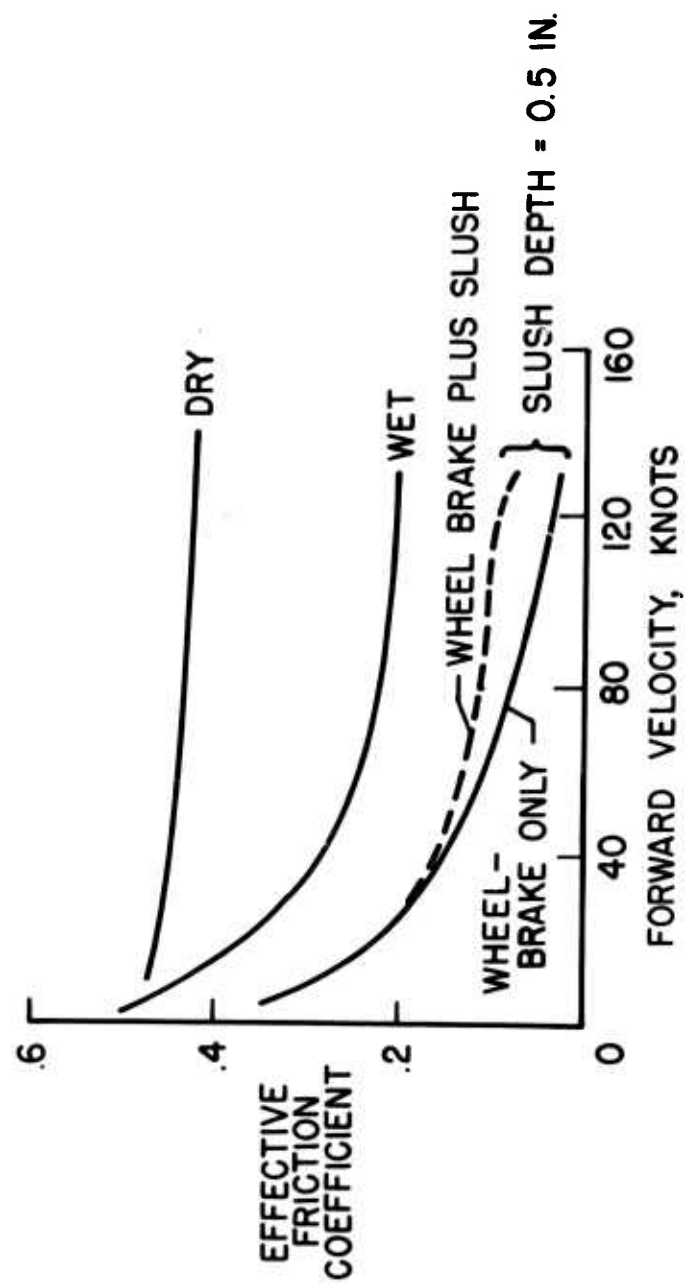


Fig.13 880M airplane braking on concrete runway

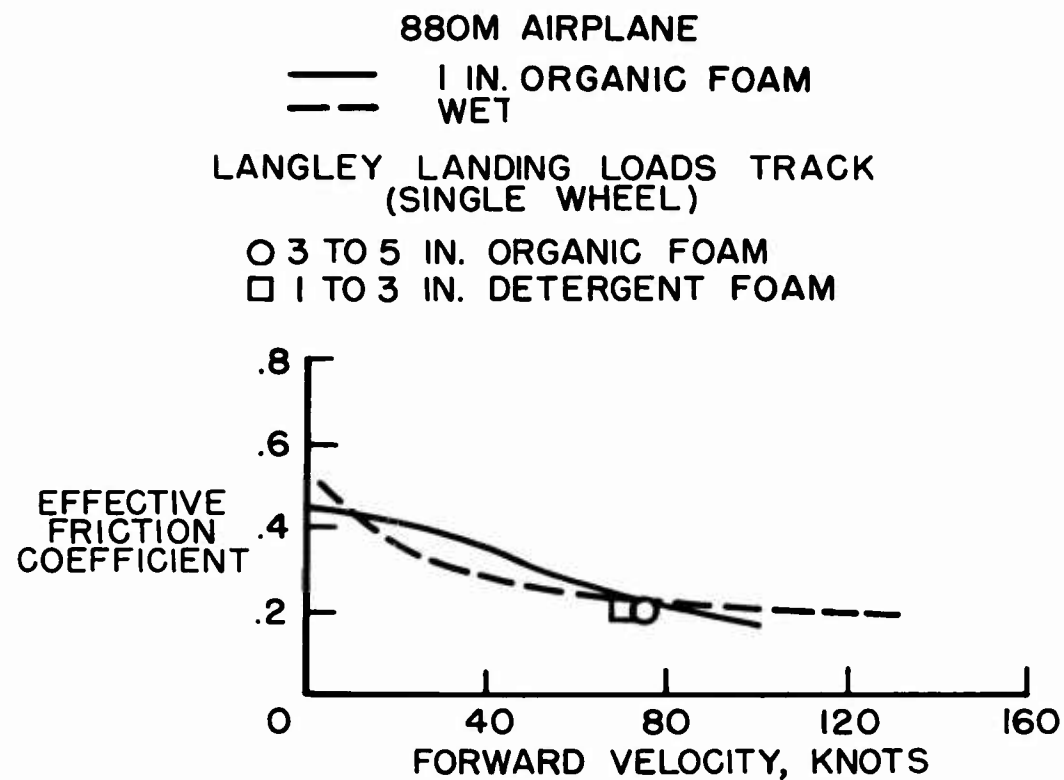


Fig. 14 Braking on wet and foam-covered concrete runways

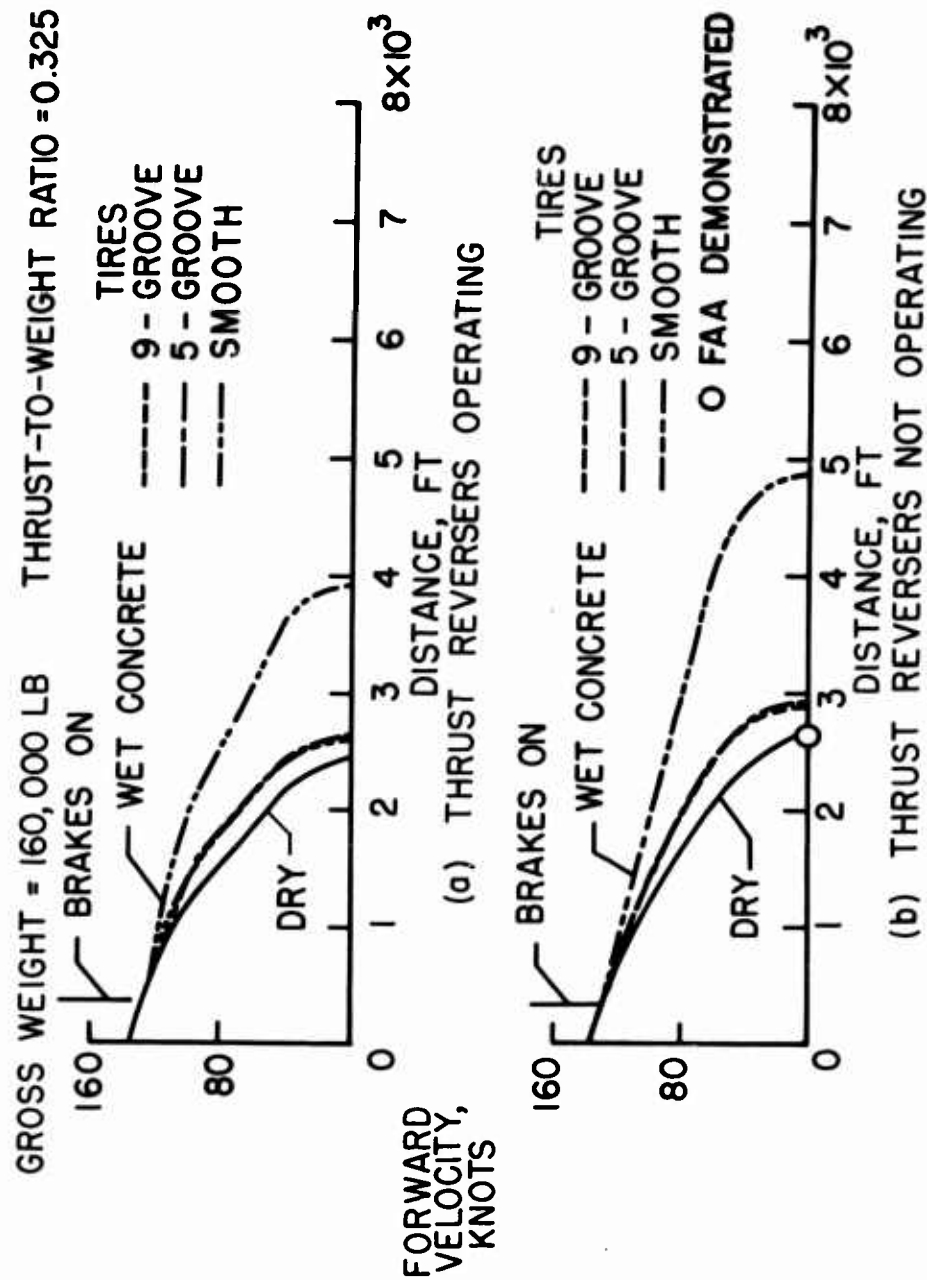


Fig. 15 Stopping distance for four-engine jet transport

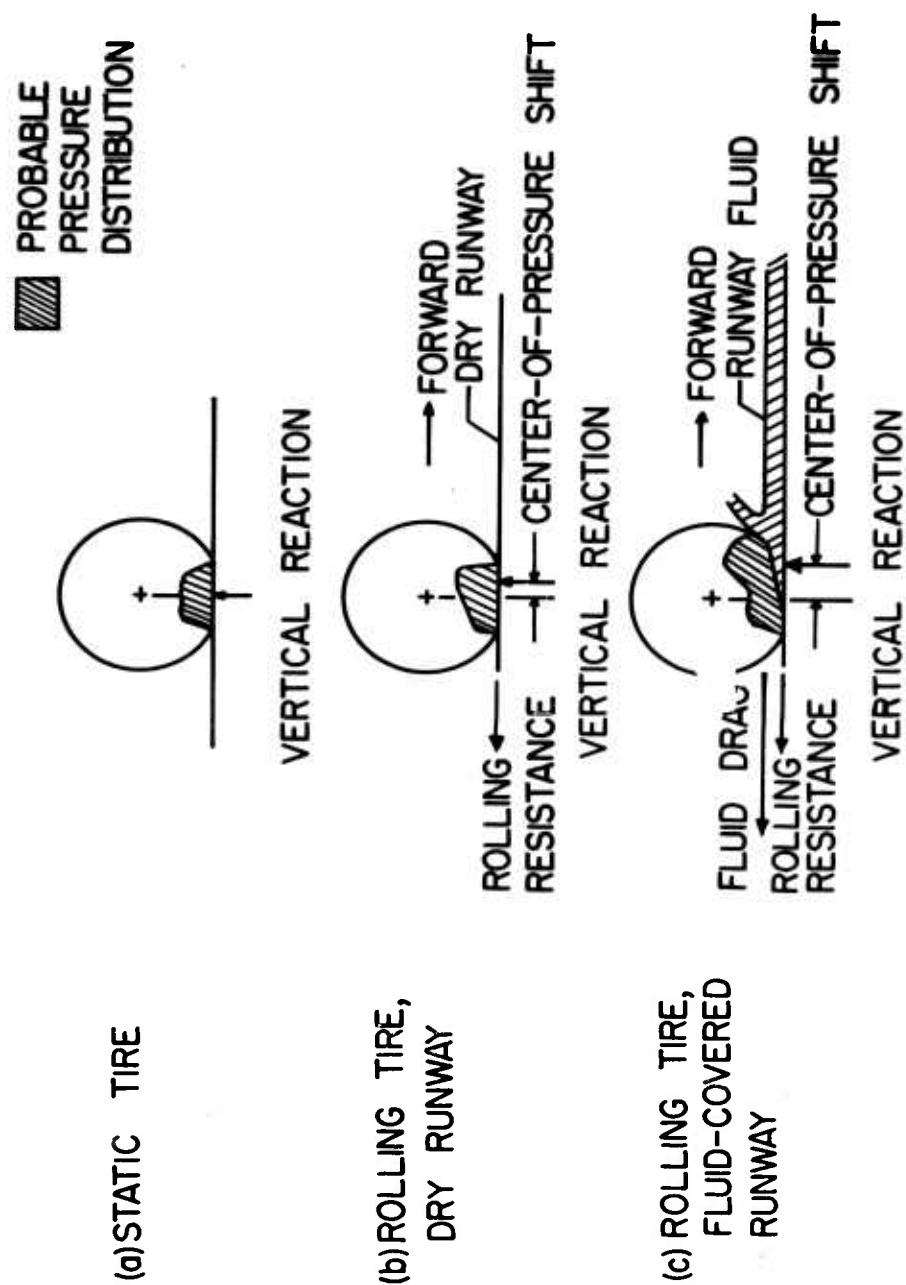


Fig. 16 Schematic of forces acting on a rolling tire

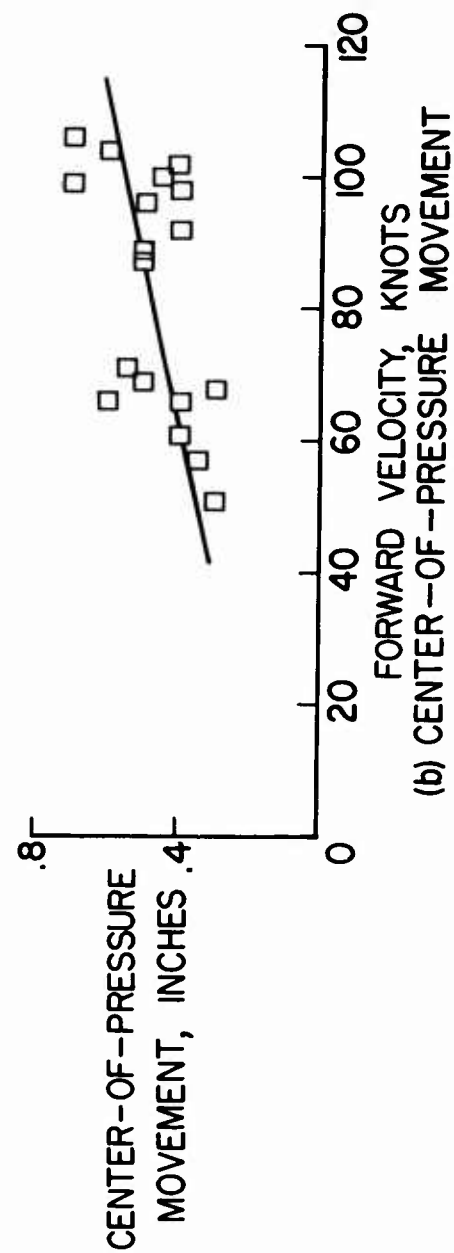
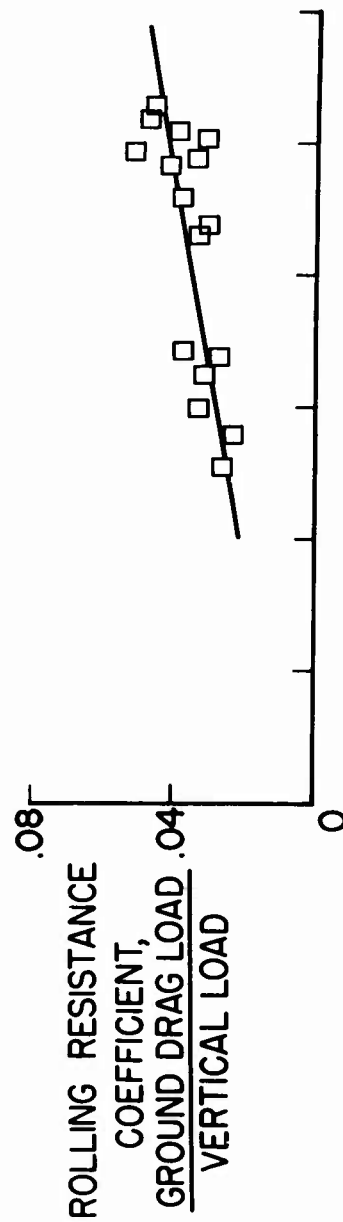


Fig. 17 Dry runway rolling characteristics

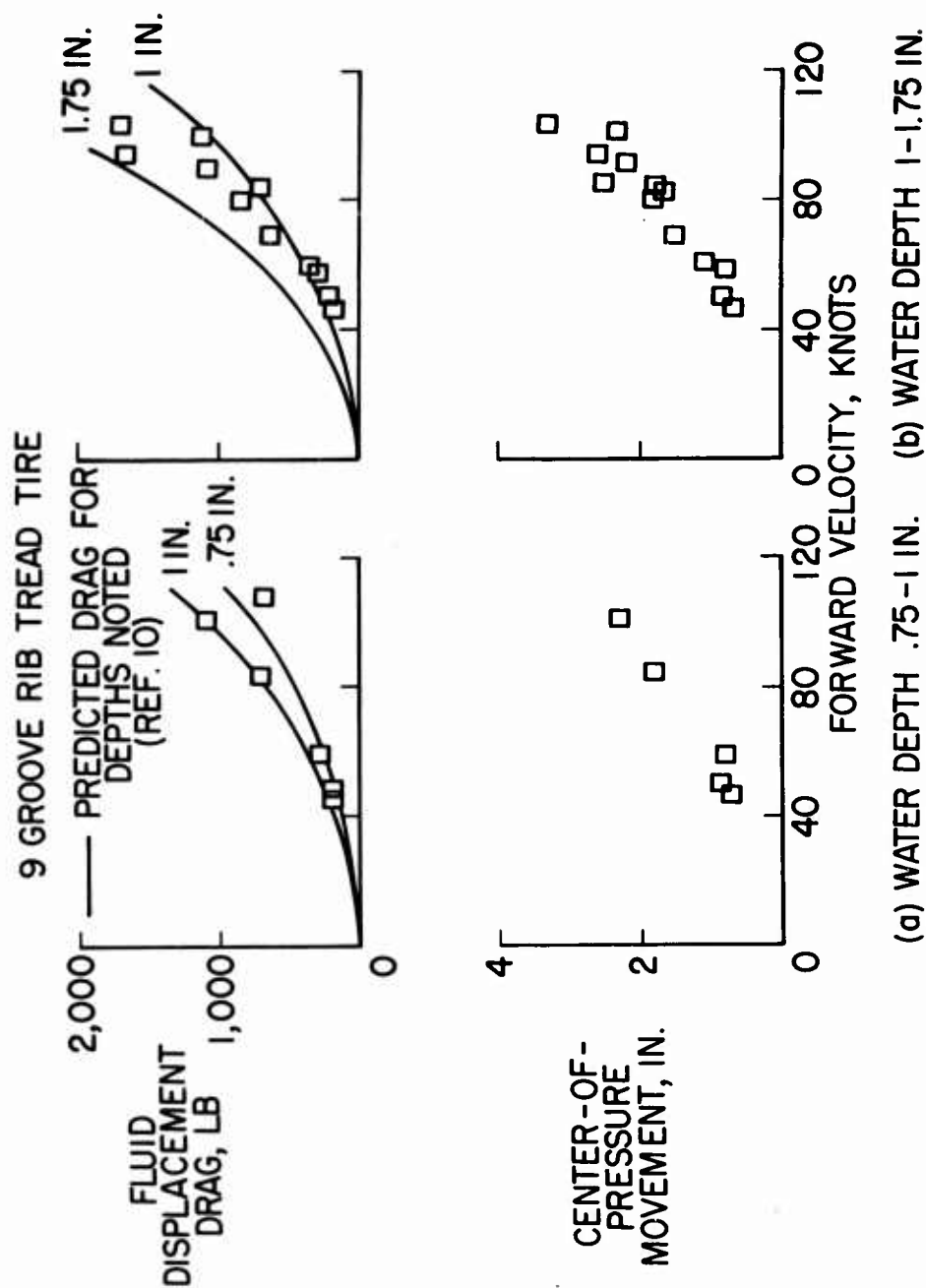


Fig. 18 Fluid-covered runway rolling characteristics

O EXP. LANGLEY LANDING LOADS TRACK
 — CALC. (REF. 10)

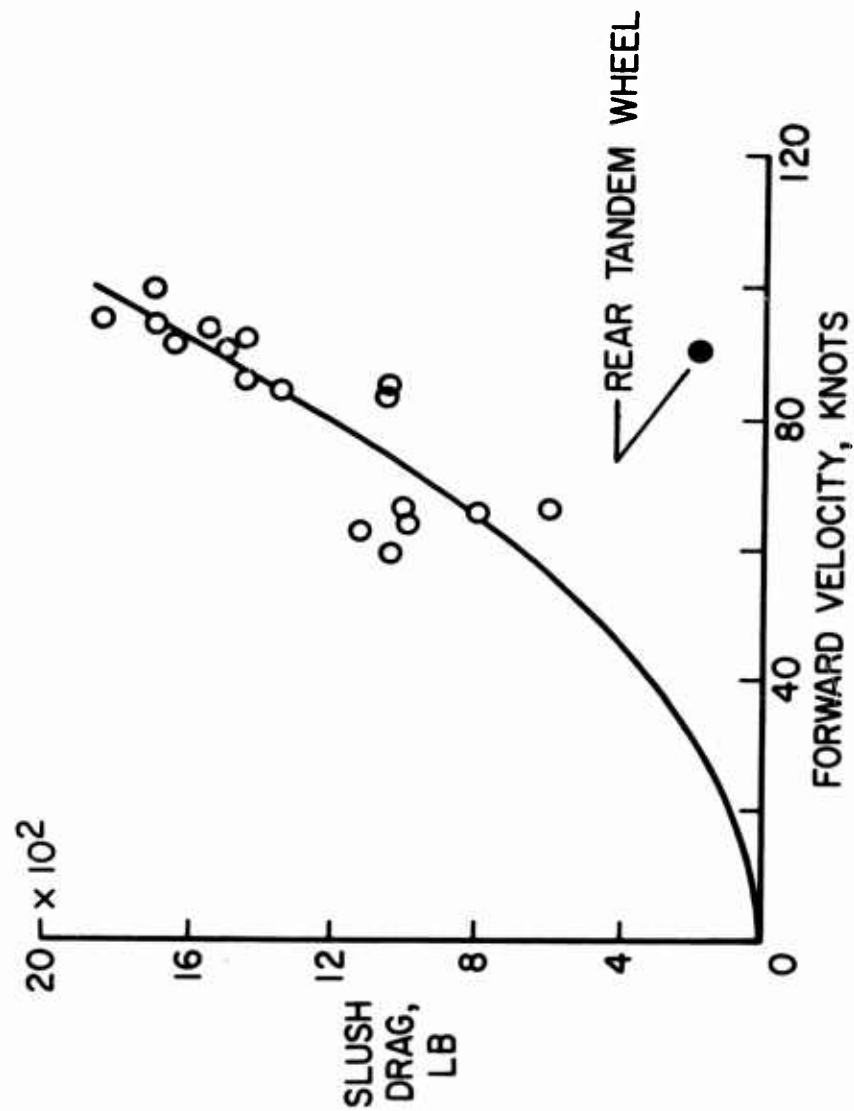


Fig. 19 Slush drag on single wheel

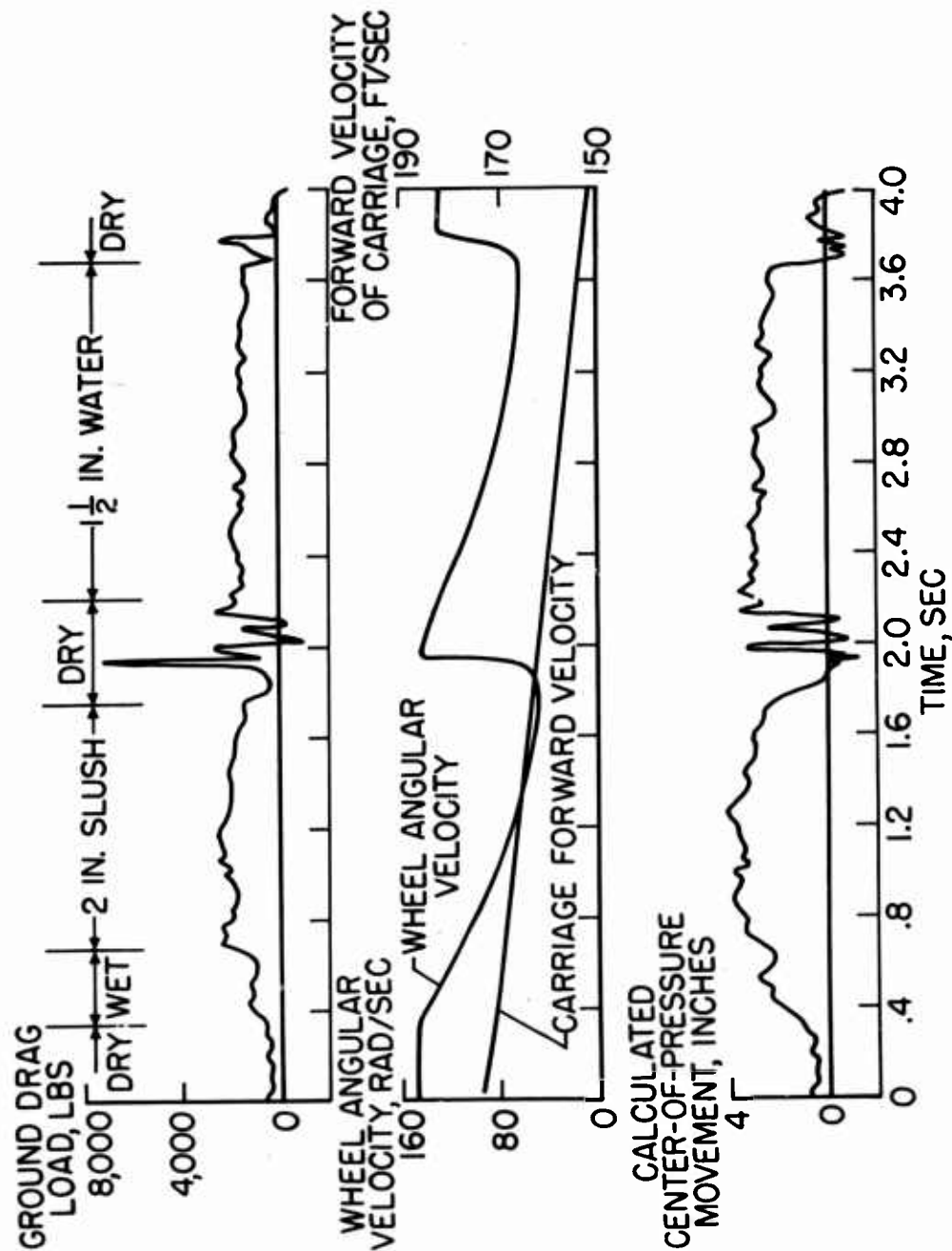


Fig. 20 Typical time-history of free-rolling single-wheel test

SLUSH SPECIFIC GRAVITY, 0.82

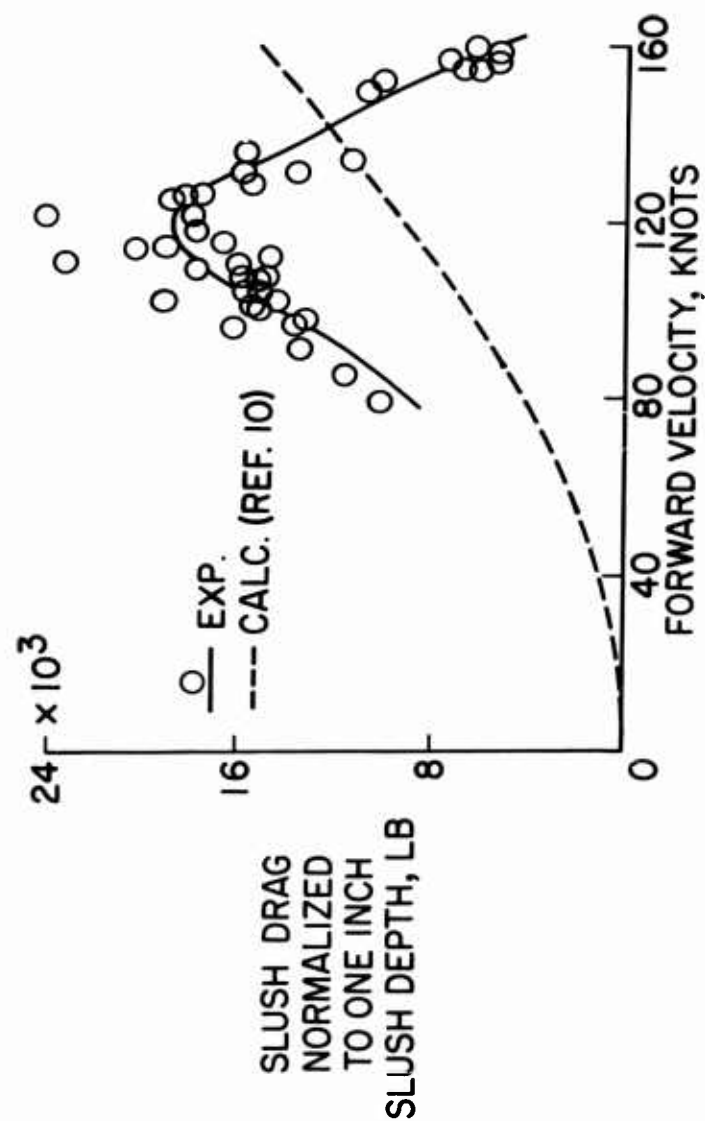


Fig. 21 Slush drag on 880M aircraft

THRUST-TO-WEIGHT RATIO = .232 GROSS WEIGHT = 193,000 LBS

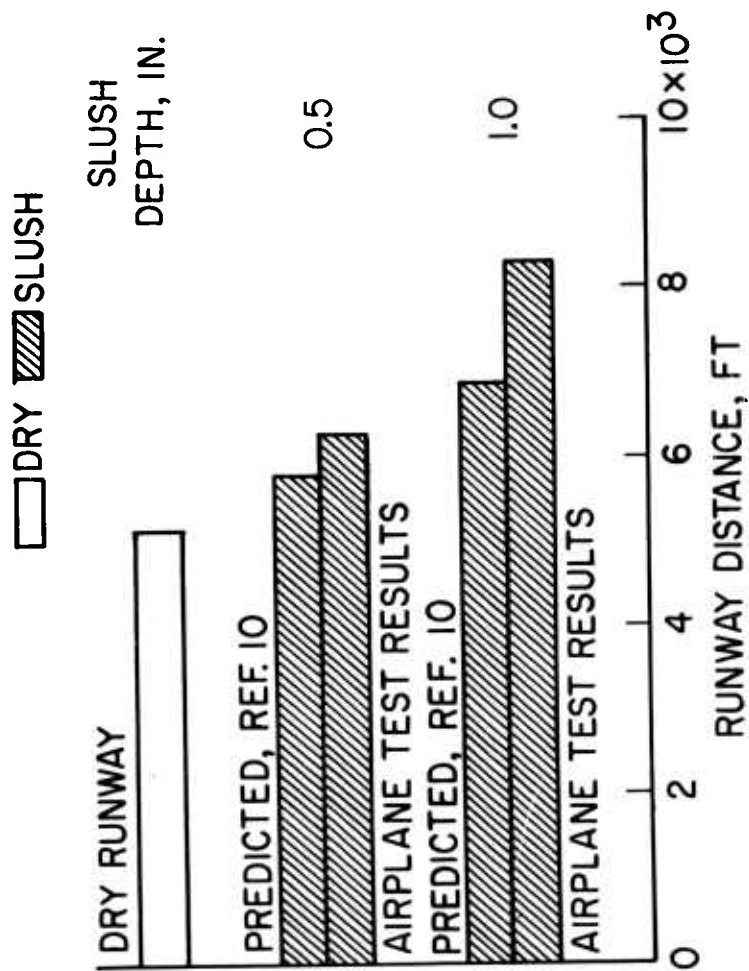


Fig. 22 880M airplane take-off distance

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<p>AGARD Report 429 North Atlantic Treaty Organization, Advisory Group for Aeronautical Research and Development INVESTIGATIONS ON THE GROUND PERFORMANCE OF AIR- CRAFT RELATING TO WET RUNWAY BRAKING AND SLUSH DRAG Upshur T. Joyner, Walter B. Horne and Trafford J.W. Leland. 1963 34 pages, incl. 12 refs. & 22 figs.</p> <p>A review is made of recent research in the U.S. relating to the ground performance of aircraft. The NASA Landing Loads Track at the Langley Research Center is briefly described, together with its capabilities. Various factors affecting landing and take-off distances are discussed and</p> <p>P. T. O.</p>	<p>533.6.015.1/2:629.139.1 3c6c 3e3b2</p>	<p>AGARD Report 429 North Atlantic Treaty Organization, Advisory Group for Aeronautical Research and Development INVESTIGATIONS ON THE GROUND PERFORMANCE OF AIR- CRAFT RELATING TO WET RUNWAY BRAKING AND SLUSH DRAG Upshur T. Joyner, Walter B. Horne and Trafford J.W. Leland. 1963 34 pages, incl. 12 refs. & 22 figs.</p> <p>A review is made of recent research in the U.S. relating to the ground performance of aircraft. The NASA Landing Loads Track at the Langley Research Center is briefly described, together with its capabilities. Various factors affecting landing and take-off distances are discussed and</p> <p>P. T. O.</p>	<p>533.6.015.1/2:629.139.1 3c6c 3e3b2</p>
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<p>performance calculations given for a typical jet transport showing the effect of runway slush. The Report concludes with indications of areas of interest for future research.</p> <p>This Report was presented at the Aircraft Take-Off and Landing Specialists' Meeting, sponsored by the AGARD Flight Mechanics Panel, held in Paris, 15-18 January 1963.</p>	<p>performance calculations given for a typical jet transport showing the effect of runway slush. The Report concludes with indications of areas of interest for future research.</p> <p>This Report was presented at the Aircraft Take-Off and Landing Specialists' Meeting, sponsored by the AGARD Flight Mechanics Panel, held in Paris, 15-18 January 1963.</p>
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